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SPACE PHYSICS LABORATORY PROJECT 5629

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES, OFFICE OF AEROSPACE RESEARCH, UNITED STATES AIR FORCE, L. G. HANSCOM FIELD, MASS.

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Abstract

The subject of Radio Astronomy is reviewed from both the historical and instrumentation viewpoints. Problem areas and fruitful areas are noted.

Foreword

A survey of Radio Astronomy techniques and capabilities was undertaken for the Electronics Research Directorate of AFCRC in early 1960 by A. W. Barber and J. P. Mullen of the Systems Analysis Office. At the suggestion of Dr. Jules Aarons, chief of the Radio Astronomy Branch of the Space Physics Laboratory, this report was re-edited and printed.

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Radio Astronomy—a Survey

1. INTRODUCTION

A.W. Barber

Twenty-eight years ago in April 1933, Karl Jansky presented a paper, "Electrical Disturbances Apparently of Extraterrestrial Origin," at the International Scientific Radio Union, Washington, D.C., in which he concluded:

> 'Data have been presented which show the existence of electromagnetic waves in the earth's atmosphere which apparently come from a direction that is fixed in space.'

Although the importance of his paper was unrecognized for a long time, Jansky had discovered a new physical phenomenon which was eventually to lead to the growth of a new scientific discipline, Radio Astronomy. An applied research project established to improve transoceanic radio communications had led to a fundamental discovery in the field of pure science.

The field of radio astronomy has had an erratic growth. In 1933, the news of Jansky's discovery received a front page spread in the New York Times and a special radio program on the subject was presented on the Blue network which included "this radio hiss from the depths of the universe."

Despite this publicity, little attention was paid to the discovery by astronomers or other members of the scientific community. As Jansky was considered to have become an authority on interference, Bell Laboratories called upon him to eliminate

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interference whether it came from stars, motor boats, or diathermy machines. A co-worker explained:

> "We decided there was no reason to go further. The noise figure for space had been established; we knew how much static to expect. We are working for a public utility and our purpose is to improve telephone service. We decided the work should be done somewhere else, at universities or in government laboratories." (Pfeiffer, "Our Changing Universe")

Nearly a decade passed during which Jansky's discoveries were largely ignored by the scientific community. A newspaper consulted a number of astronomers and reported them as saying:

> "It is hard to believe... We infer a transmitting station of such staggering dimensions and energy that even an astrophysicist would hesitate to set down the billions and billions of kilowatts that must be radiated to register on the earth even the feeble effects noted by Dr. Jansky."

During this time, a single man, Grote Reber, carried forward the field of radio astronomy in his spare time and at his own expense. In 1933, while a student at Illinois Institute of Technology, Reber attempted to bounce signals off the moon with a 10- and then with a 40-watt transmitter. When this failed, he turned to radio astronomy after reading Jansky's paper. Realizing that a large steerable parabolic antenna would be needed, he undertook the construction of a 31-ft antenna in his backyard in Illinois in the summer of 1937. Having rejected the $ 7,000 bid of the American Bridge Company as too expensive, he personnaly designed and constructed the antenna from forty sections of galvanized iron mounted on a bowl-shaped wooden framework.*

Reber carried out numerous experiments with this equipment from midnight until 6:00 a.m., recording the readings of a microammeter every minute. He would then drive thirty miles to Chicago where he was employed designing home radio receivers. He slept in the early evening when auto ignition and other interference made measurements impossible. Reber's work was reported in three articles in the Astrophysical Journal.[1]

After World War II, a number of British and Australian scientists began significant radio astronomy work. In England, Ryle and Vonberg[2] first published interferometer measurements of radio point sources, while in Sidney, Pawsey, Payne-Scott, and McCready[3] proved the relationship between intense radio noise and sunspot activity.

*This antenna was used by Reber, for some of his work at the National Bureau of Standards from 1947 until 1952. It was then shipped to the National Bureau of Standards facility at Boulder, Colorado. Recently, it was disassembled and made available to the National Radio Astronomy Observatory. When disassembled, Reber noted, "all pieces were dry, solid, and as good as when put together. With reasonable care it could have lasted indefinitely." The construction cost of this antenna was $2,000.

By the early fifties, many other groups had been established throughout the world including the Netherlands, France, Japan, and Russia. In this country, the leading American groups were at Harvard, Cornell, and Ohio State Universities, and at the Naval Research Laboratory and Carnegie Institute in Washington. With the advent of the Space Age in 1957, radio astronomy became not only permissible but glamorous. Radio astronomy groups have come into existence in many locations in the United States. Indeed, it has appeared to our European friends that 85-ft parabolas have sprouted like weeds in this country during the past three years. Certainly, radio astronomy has come of age in the United States in terms of quantity if not quality.

When recently asked to make a speech, Reber wrote:

> "I take a dim view of speech-making... Jansky suffered from poor health, he talked without visible success. As he explained to me at one time, the electrical engineers were not interested because they didn't know any astronomy and couldn't find anything useful in the subject. The astronomers were not interested because they didn't know any electrical engineering and considered their present techniques adequate for the study of the Universe...
> It now appears that our savants have discovered radio astronomy through the efforts of the British and Australians. This bears out a statement by Kettering to the effect that the best way to get the inventions of the General Motors Laboratories into General Motors cars was for Chrysler or Ford to start using them."

Today, more than twenty-five years after the first radio astronomy measurements were made in this country, the United States Air Force is just beginning to have an integrated radio astronomy program. It is the purpose of this report to survey the field of radio astronomy in order to provide the basis for the establishment of an enhanced and effective radio-astronomy program within the Air Force Cambridge Research Laboratories, commensurate with the importance of this field to future aerospace operations. Whether the stimulation is found in the section that discusses applications of radio astronomy to aerospace operations or even from the discussion of the well-conceived and well-implemented Navy radio-astronomy program is of little import. The important conclusion is that a strong radio-astronomy program is essential if the Office of Aerospace Research is to gain the research data required to provide the Air Force with superior aerospace weapons of the future.

2. SOLAR RADIO STUDIES

A.W. Barber

On February 27, 1942, the British early warning radar system was jammed so effectively that for a time the British believed the Germans had suddenly developed a new jamming device. Despite the continued jamming for forty-eight hours there were no Nazi attacks. When the jamming disappeared a mystery remained. Mr. Stanley Hey, a member of the operations research group in London (ECM Section), collected reports on the phenomena from Southampton, Yarmouth, Bristol, and Hull.

After analyzing the reports, he prepared a classified memorandum. The interference, he found, was coming not from German sources but from the sun. The disturbance faded after the passing of a large sunspot.

This was the first documented record of solar radio waves. Later the same year, at the Bell Telephone Laboratories Dr. G.C. Southworth independently measured solar radiation and prepared a paper on the subject. As both Hey's and Southworth's work were classified, Grote Reber's[1] discovery of solar radiation at 160 Mcps in 1943 was the first published account of solar radiation.

Six months later on 29 June, Southworth attempted to measure radio emission from the sun using radar equipment. He succeeded at 10,000 Mcps and at 3,000 Mcps. These measurements were the first quantitative radio studies of the quiet sun.

Hey noted, in reporting his work:[4]

> The noise power received from the sun was of the order of 10^{-3} watts per square meter per megacycle bandwidth. This unusual intensity, of the order of 10^{5} times that corresponding to the calculated black body radiation, appears to have been associated with the occurrence of a big solar flare reported to be in a central position on February 28, 1942.

J.L. Pawsey, R. Payne-Scott, L.L. McCready carried out a series of observations on 1.5 meters from a 400-ft hill overlooking the city of Sydney in October 1945. While their measurements were relatively crude, they clearly established the correlation between radiation at 1.5 meters and sunspot density.[5]

> It is apparent that the peaks of 1.5 meter radiation coincide with peaks of the sunspot area curve and with the passage of large sunspot groups across the meridian. This strongly suggests a physical relationship between the two phenomena, as suggested by the British Army observers. Observations were also made at sunrise on October 4th and 5th on 50 centimeter and 25 centimeter equipment. On 50 centimeter wavelength no effect was observed, indicating an "equivalent temperature" of less than 50,000°K; on 25 centimeters a small effect was observed corresponding to about 6,000°K, the actual temperature of the sun.

Between 20 July and 1 August 1946, Martin Ryle and D.D. Vonberg made the first measurements of the size of a radio emitting region on the solar surface. They used an interferometer having a spacing of 140 wavelengths. The maximum to minimum ratio indicated a source diameter of ten minutes of arc.[2]

> The maximum to minimum ratio obtained under these conditions corresponds to a source diameter of ten minutes of arc. Any inequalities in the two aerial systems would result in an overestimate of diameter and this is therefore a maximum value. Since the value obtained does not greatly exceed the diameter of the visual spot, it is reasonable to relate the source of this radiation with the visual spot itself, or a region closely associated with it.

Ryle noted that the radiation from a source of this diameter corresponded to a temperature greater than 2×10^{12} °Kelvin. Furthermore, the radiation was strongly circularly polarized. He concluded, "It will be necessary to collect more experimental data before possible theories can profitably be considered in detail." In

July 1946, Ryle and Vonberg with D. F. Martyn[6] made observations of solar polarization at 200 Mcps, finding noise storms strongly circularly polarized.[5]

One of the early fundamental solar radio problems was the apparent different blackbody temperatures of the sun when measured at different frequencies. Pawsey et al.[3] reported late in 1946:

> This radiation has characteristics similar to those of thermal radiation but is always hundreds of time greater than the thermal radiation anticipated from the photosphere and sometimes greater by a factor of 10^4... there appear to be two distinct types of variation, a relatively slowly varying type with intensity ranging from about 5×10^{-15} to 100×10^{-15} watts per square meter (per megacycle per second) and a type consisting of intense bursts of duration of between a fraction of a second and a minute.

They also observed that:

> directional observations... indicate that the radiation originates not uniformly over the sun's disk but in restricted areas in the immediate vicinity of a sunspot group.

It is interesting to note that the sun's departure from blackbody radiation had been noted earlier. E. V. Appleton wrote:[7]

> The object of this communication is to point out that there is evidence from radio reception experience dating from the period of the last sunspot maximum which suggests that during periods of marked solar activity, the sun occasionally emits radiation in the radio spectrum greatly in excess of blackbody radiation corresponding to 6000°K...
>
> My attention was first attracted to this phenomenon of abnormal solar radiation by Mr. D. W. Heightman (Amateur Station G6DH) who described hearing in 1936 a hissing sound when receiving in the range of 10-40 megacycles. Other amateur observers sent me further excellent reports, from which I concluded that the noise was due to the emission of electromagnetic radiation from active areas on the sun... It is easy to show that this (the sun's) power is only about 10^{-4} of the receiver noise associated with earth surface temperature and for that reason solar radiation does not obtrude in wireless receivers of ordinary type... When the noise was observable, the intensity of the solar radio flux from the active area was about 10^4 times that associated with the blackbody radiation from the disk as a whole.

Earlier optical measurements had clearly shown the sun's surface or photosphere to have a temperature of 6000°K.

While at this time there was general agreement that solar disturbances created the increased noise level, there was great difficulty in developing a physical model of the transmissions because of a lack of correlation between most bursts. Strong bursts would occasionally correlate on two adjacent frequencies, being similar in shape and nearly coincident in time. On 8 March 1947, Payne-Scott, Yabsley, and Bolton reported measurements of a solar flare from which measurements were made on 200, 100, and 60 Mcps in which:

> There was a delay of 2 minutes between the onset of the outburst on 200 and 100 megacycles and 4 minutes between 100 and 60 megacycles.

The Australians then showed that this led to assumptions that the signals coming from the flare originated from different portions of the solar atmosphere as the exciting material moved outward. The 200 megacycle signals were shown to have

originated at the base of the corona, the 100 megacycle signals originated at a height of 90,000 km, and the 60 megacycle signals 200,000 km above the base of the corona. Calculations showed that the propagation medium moved at a speed of 750 km/sec between the first and second observations and 500 km/sec between the second and third measurements. It was thus possible to associate a frequency with a given level in the sun's atmosphere.

Payne-Scott observed that the majority of unpolarized bursts of solar noise on frequencies 60 to 100 Mcps show a definite double humped form. Jaeger and Westfold showed that this could be caused by transmission along two paths, the direct path and an "echo" path, within the solar corona. The echo contributed the second smaller hump.

Measurements of the quiet sun have shown distinct variations in effective temperature. At centimeter wavelengths (30,000 Mcps) the apparent blackbody temperature is less than 10,000°K while at meter wavelengths the temperature is well over 1,000,000°Kelvin. Martyn, who proposed the first satisfactory explanation, suggested that different frequencies originated in different layers of the sun's atmosphere. From optical measurements of the sunlight scattered by the corona it is possible to calculate the free electron density at various distances from the solar surface. For example, at a distance of 430,000 miles above the sun's surface the electron density has dropped to one million electrons per cubic centimeter, which is comparable to F-layer density.

In July 1946 at the Australian Commonwealth Observatory, Martyn made measurements of the polarization of sunspots with four yagi antennas. He reported:[6]

> It was found that the right-handed circularly polarized power received was some seven times greater than that received when the system accepted only left-handed circularly polarized radiation... Three days later, when this spot group had crossed the meridian, these conditions were reversed, five times more power being then received on the left-handed than on the right-handed system.

Numerous measurements were made of the radiation from the sun at various frequencies. Southworth carried out measurements at 1.3 and 10 cm. Dicke and Beringer made measurements at 1.25 cm and others were made by Sanders at 3.2 cm. Other measurements were made by Reber (62.5 cm), Covington (10.7 cm), and Lehany and Yabsley (25 and 50 cm). The higher frequencies were explored by Minnett and Labrum at 3.18 cm.

The next major advance came with the contribution of Wild, of CSIRO in Sydney, who analyzed the radio spectrum of various types of solar noise burst. Wild concluded, "Outbursts conform, in some cases at least, to a distinct spectral type and can therefore be recognized at once from a record of the spectrum." These he classified as follows:[8]

1. Type I burst: This is a circularly polarized radiation which predominates during noise storms. It is closely correlated with the movements of sunspots. This

radiation shows little or no correspondence with frequencies separated more than a few megacycles.

2. Type II burst or slow drift bursts: This burst shows a very sharp lower frequency cutoff below which no radiation is received. The critical frequency drifts slowly toward lower frequencies at the rate of approximately 1/4 Mcps sec^{-1}. The drift rate is independent of frequency. This burst lasts for several minutes and often but not always coincides with a solar flare.

3. Type III burst or fast drift bursts: This is a broadband noise usually not less than 50 megacycles wide which drifts toward the lower frequencies at a rate of approximately 20 Mcps sec^{-1}. Type III bursts last for only a few seconds.

Wild concluded that the surge prominences which are observed on the sun with velocities of 100 to 200 km/sec could explain the slow moving bursts, while particles emitted from the sun that cause magnetic storms on earth could be associated with the fast moving particles that have velocities of 800 to 1600 km/sec. He wrote:[8]

> Two pieces of evidence may be significant...the fact that frequency drift has been observed only in one direction corresponding to outward motion; and the indication that the typical drift corresponds to acceleration outwards. The suggestion is therefore of an accelerating outrush of matter that escapes completely from the sun. This evidence does not support that the agency corresponds to visible matter seen in a surge prominence, the leading edge of which normally travels out to a height of about 10^5 kilometers above the photosphere and then falls back to the sun. It may however correspond to matter which escapes visual detection because of its high degree of ionization. The evidence seems quite consistent, both qualitatively and quantitatively, with the hypothesis that the agency corresponds to the particles that cause the terrestrial magnetic storms.

3. FROM THE EARTH TO THE PLANETS--UPPER ATMOSPHERE RADIO OBSERVATIONS

J. P. Mullen

The radio environment above the earth will be discussed using the demarcation suggested by Chapman and the International Union of Geodesy and Geophysics.*

0 - 7 miles	Troposphere
7 - 20 miles	Stratosphere
20 - 50 miles	Mesosphere
50 - 300 miles	Ionosphere
300 - 500 miles	Thermosphere
500 and beyond	Exosphere

These regions, described in Table 1, are characterized by several factors which in turn may subdivide the atmosphere mass. The classification listed above is on the basis of temperature, ionization, and molecular escape. A representation of electron density is shown in Figure 1. This curve taken from the Handbook of Geophysics,*

*Handbook of Geophysics for Air Force Designers, Geophysics Research Directorate, Air Force Cambridge Research Center, ARDC, 1957, 1st ed.

TABLE 1. Description of Atmospheric Regions

Name	Description
	Temperature
Troposphere	The region nearest the surface, having a more or less uniform decrease of temperature with altitude. The nominal rate of temperature decrease is 6.5°K/km, but inversions are common. The troposphere, the domain of weather, is in convective equilibrium with the sun-warmed surface of the earth. The tropopause, which occurs at altitudes between 6 and 18 kilometers (higher and colder over the equator), is the domain of high winds and higher cirrus clouds.
Stratosphere	The region next above the troposphere and having a nominally constant temperature. The stratosphere is thicker over the poles, thinner or even nonexistent over the equator. Maximum of atmospheric ozone found near stratopause. Rare nacreous clouds also found near stratopause. Stratopause is at about 25 kilometers in middle latitudes. Stratospheric temperatures are in ther order of arctic winter temperatures.
Mesosphere	The region of the first temperature maximum. The mesosphere lies above the stratosphere and below the major temperature minimum which is found near 80 kilometers altitude and constitutes the mesopause. A relatively warm region between two cold regions; the region of disappearance of most meteors. The mesopause is found at altitudes of from 70 to 85 kilom eters. Mesosphere is in radiative equilibrium between ultraviolet ozone heating by the upper fringe of ozone region and the infrared ozone and carbon dioxide cooling by radiation to space.
Thermosphere	The region of rising temperature above the major temperature minimum around 80 kilometers altitude. No upper altitude limit. The domain of the aurorae. Temperature rise at base of thermosphere attributed to too infrequent collision among molecules to maintain thermodynamic equilibrium. The potentially enormous infrared radiative cooling by carbon dioxide is not actually realized owing to inadequate collisions.
	Ionization
Ionosphere	The region of sufficiently large electron density to affect radio communication. However, only one molecule in 100 or 1000 in the F_2 region to one in 100,000,000 in the D region is ionized. The bottom of the ionosphere, the D region, is found at about 80 kilometers during the day. At night the D region disappears and the bottom of the ionosphere rises to 100 kilometers. The top of the ionosphere is not well defined but is often taken as about 400 kilometers.
	Molecular Escape
Exosphere	The region wherein molecular escape from the earth's atmosphere is significant. The base of the exosphere, the critical level, is thought to be at an altitude above 300 kilometers, possibly as high as 1000 kilometers. Lighter atoms and molecules can escape at lower altitudes than heavier ones. The earth's magnetic field effectively prevents the escape of charged particles, however.

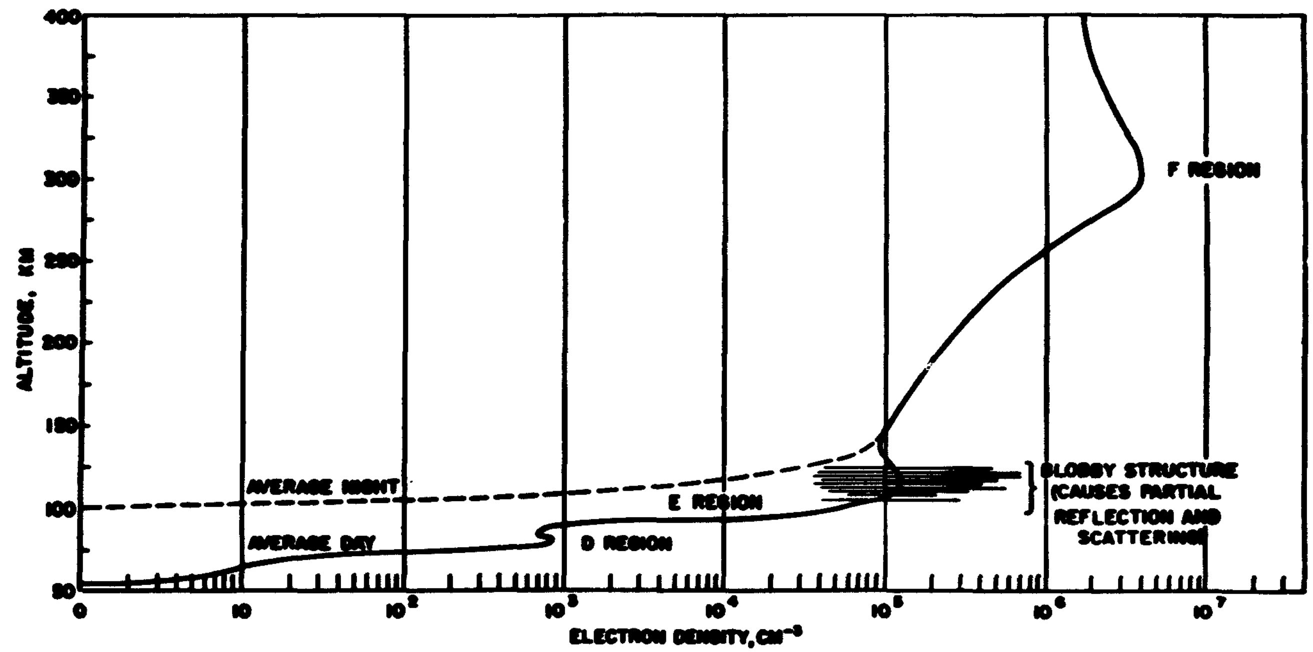

Figure 2. An Electron Density Model in the Ionosphere

is by no means absolute, for the electron density is a function of many variables including time of day and season, geographical positions, and solar disturbances, to name only a few of the better known.

The magnitude of the electron density above the ionosphere is quite unknown. Estimates at one or two earth radii (4000 to 8000 miles) are 10^2 to 10^3 electrons per cubic centimeter. The sensitivity of the Arecibo radar (the 1000-ft radar telescope currently under construction in Puerto Rico as a joint project of Cornell University and AFCRL) has as a design objective the detection of electron densities of a thousand or so at two earth radii. Such a tool would supplement a rapidly growing complement of rocket probes, satellite instruments, ionospheric sounders, and ionospheric radars. Here it should be noted that AFCRL plans to instrument a satellite which will carry an ionosonde (a radar-like device to measure ionosphere height as a function of frequency) to look down on the ionosphere and probe it from the top side.

The work of Bowles should also be noted; he and his colleagues at the National Bureau of Standards have built a huge radar at Havana, Illinois, and at Huancayo, Peru and measured returns scattered incoherently from particles in the F layer of the ionosphere. The Lincoln Laboratory of MIT also has an extensive program of radar studies of ionospheric particles.

The contributions of the methods of radio astronomy to the study of the earth's atmosphere and ionosphere have been many. The observation of the sun and other stars has told us a great deal about the frequency and angle dependence of the troposphere and ionosphere; use of several receiving points for a single source, for example, confirmed the blobby structure of the ionosphere. Experiments to be performed will locate and track clouds of ionized gas ejected from the disturbed sun, thereby predicting magneto-ionic disturbances on the earth.[9] Since the transit time is on the order of one or two days, this much warning may be obtained. These experiments will use the powerful radar set up by the National Bureau of Standards at Huancayo, Peru, looking perpendicular to the earth's magnetic field, and, in addition to tracking solar winds, will yield data on electron density, ion kinetic temperature, composition of ionic components, magnetic-field intensity and ionospheric turbulence (D layer).

3.1 Meteors

Meteors are particles of interplanetary matter which collide with the earth's atmosphere causing a streak of hot gas as they are vaporized by the air friction. First considered local phenomena, the visible streaks, or "shooting stars" as they are popularly called, have been accepted as having astronomical significance, and have been studied as such for over a hundred years. Meteors are quite common

phenomena; billions of them occur each day. They occur in random fashion as well as in showers; the latter are identified with a constellation toward which their paths appear to converge. If we trace back the paths of a meteor shower, parallax causes them to appear to converge to a point, called the radiant. The constellations in which these radiants lie are used to identify the showers. Some of the more common showers are the Leonids whose radiant lies in the constellation Leo; the Taurids from Taurus, the Perseids from Perseus, the Draconids from Draco, the Lyrids from Lyrus, to name only a few.

The origin of the meteors is, of course, unknown; however, it has been 'determined' from their velocities that practically all of them are on elliptical orbits, since they lack the velocity to travel the parabolic or hyperbolic path needed to escape the solar system.* While optical techniques, largely pioneered by the Harvard Observatory, have established the scarcity of parabolic velocities, their operation has been fairly slow and time consuming. Radio and radar techniques, on the other hand, have yielded fast and accurate information in great volume. These techniques are independent of time of day and weather, and yield accurate information on trajectory and velocity.

In order to compare the rapidity of data acquisition, it can be said that optical means have furnished complete data on 4000 meteors in about 30 years. Radar observations, on the other hand, have furnished millions of observations within a couple of years. The fact that radar is independent of weather and time of day is only partially responsible for the difference; optically, two simultaneous observations from remotely located equipment are needed, while radar observations generally require only a single location, a powerful advantage.

The origin of meteors is subject to speculation. It has been estimated from observed spectra that they contain traces (upon occasion) of iron, calcium, magnesium, manganese, chromium, silicon, nickel, aluminum, and sodium. Meteorites (that is, those interplanetary objects which have survived re-entry), have been analyzed and have been found to contain (again on occasion) magnesium, calcium, sodium, and aluminum.[10] There is little doubt that meteor showers or swarms are associated with comets (which are large bodies whirling through the solar system on orbits varying from 3.3 years to centuries). There is, however, some question of the exact nature of this association; whether the showers are caused by fragments of a disintegrating comet, or whether they are separate entities traveling with the comet, or whether the comet is, in fact, a condensed group of particles from a meteor swarm.[11]

Table 2 [10] presents an estimate of the type and mass of meteoric material falling on the earth.

*At the earth's distance from the sun, the velocity of a body in a parabolic path is 42.1 km (26.1 mi.) per second. Objects moving at this or a greater velocity cannot be permanent members of the solar system.

TABLE 2. Daily Rate of Meteoritic Infall

Type	Mass accumulated daily (tons)
Crater-producing and other meteorites	< 1
Fireballs Visual meteors Faint radio meteors Telescopic meteors	1 - 10
Very faint telescopic meteors Micrometeorites Interplanetary dust	1,000 - 10,000

From this table one may gather that the earth grows each day by over a thousand tons, or 5 to 10 pounds per square mile.

3.2 The Moon

Earth's moon has been a source of wonder and conjecture to man since ancient times, as might be expected of a body 27.3 percent as large (in diameter) as our earth and located only 240,000 miles away. The moon has been probed passively, that is, by observing the reflection of the sun's radiation, for centuries, and very recently, by observing the reflection of radio energy with which it has been illuminated from earth. We are told that the earliest successful attempts to observe radar-like reflections from the moon were made in 1946 by Z. Bay in Hungary, and, independently, by the U.S. Army Signal Corps at Ft. Monmouth. Details of Bay's equipment are unknown except that his indicator was a bank of water-voltameters which he switched at regular in tervals with an integrating time of 30 minutes; the method could perform detection at signal to noise ratios of 0.1. The Signal Corps equipment used 3 kw peak power into a 26-db antenna at 116 Mcps.

The Australians performed a similar experiment in 1947, using the 70-kw Radio Australia broadcast transmitter on 20 Mcps, and receiving from a site about 400 miles away. Experim ents at Jodrell Bank have been performed using a 10-kw radar at 120 Mcps, beginning in 1955.[12] Later work has been done transmitting from Jodrell Bank using the 250-ft telescope and receiving with the 84-ft telescope at the Hamilton site of AFCRL, as well as extensive lunar work at NRL under Yaplee and others at frequencies from 20 to 2900 Mcps. One might ask what secrets these experiments have divulged. We have learned that the surface of the moon has a low thermal conductivity. We are able to theorize that it is covered by a layer of dust at least 2 cm deep. The topography has been revealed by the pulse length distortion measured in radio returns. The radar reflectivity has been estimated to be 0.1.

The fading of moon echoes also furnishes some data on libration, that is, the rocking of the moon on its axis. More recently, polarization studies of lunar echoes were accomplished during the solar eclipse of October 1959.[13] Measurements of the lunar atmosphere by occultation techniques indicate that it is less than one trillionth of that of our earth, the precision of this information being an improvement by a factor of 1000 over that previously available.

The moon, despite its somewhat adverse reflection characteristics has been used as a mirror for communications purposes. Several reports on this subject have been written at AFCRL.

3.3 Observations of Radio Emission From the Planets

As we have seen in Section 2, the sun is a very rich emitter of radio waves. Thermal radiations from the moon have, however, been reported, thermal and non-thermal from Jupiter and Venus. The earliest report of passive detection of lunar radiation was by R. H. Dicke and Berringer[14] in 1946, using a 24,000-Mcps radiometer of the type to become almost universal and named after its inventor, Dicke. More extensive measurements were made by Piddington[15] and others of the Australian Commonwealth Scientific and Industrial Research Organization (in 1949). They found a small temperature range with lunar phase in the microwave region when compared with they of the infrared, which they interpret as evidence that the infrared temperatures are radiated from the surface and the microwave from half a meter or so beneath. At the frequency observed the temperature varied between 200°K and 300°K. At lower frequencies the variations diminish, at 400 Mcps the variation becomes less than 10 percent, which further strengthens the hypothesis of longer waves coming from deeper within the moon.

Other thermal radiation has been measured from Mars and Venus, using the Naval Research Laboratory 50-ft steerable radio telescope at a frequency of about 9500 Mcps. The estimated temperature for Mars was about 240°K, and of Venus, 500 to 600°K. There exists a certain amount of uncertainty about Venus, however, since its surface has never been seen, and the composition of its atmosphere is in doubt. Recent balloon flights have indicated the presence of water vapor in the Venusian atmosphere, which challenges the high temperatures suggested. The Mariner space craft, well on its way toward Venus and carrying a simple radiometer, will hopefully resolve the problem.

Drake and Ewen at Harvard measured the temperature of Jupiter and Saturn at 8000 Mcps, and found these in the order of 200°K. Cook and others at the University of Michigan measured the thermal radiation of Saturn at 8700 Mcps, using a maser. Their findings indicated a temperature of 106±21°K. The major problem

of planetary astronomy is that the planet subtends such a small arc of the antenna pattern, and the measured temperature is related to the normalized temperature by ratio of the source width to the beam width. Thus, the measured value may be only a thousandth of the computed value, and it can be seen that these are very close to the sensitivity limit of even the best receivers. Obviously, when operating at such extreme sensitivities, the accuracy is bound to suffer, and is, in fact, on the order of 50 percent for some measurements.

3.4 Nonthermal Emissions

Nonthermal emissions from the planet Jupiter have been reported and verified by many observers and reported but unverified from Saturn and Venus. These latter were the 27.3 Mcps work of Kraus[16] at Ohio State and the 21.1 Mcps work of Smith at Yale. Neither of these has been confirmed as yet.

A relatively large number of observations have been made on nonthermal radiation from Jupiter. These began with the detection by Burke and Franklin[17] in 1955, of an intense source of 22 Mcps radiations. After the announcement of their discovery, other researchers re-examining their own records confirmed the source. Further work isolated and determined the rotational speed of the localized source; however, it has not yet been determined whether the radio source is on or above the planet's surface. Table 3 lists the frequencies and observers of the Jupiter radiation. The radiation is of a pulsed nature and is of seconds duration. Its characteristics have been likened to that of a terrestrial thunderstorm; however, unlike a lightning discharge it usually appears to be circularly polarized. The power output, estimated to be about 10^{17} watt-seconds, is of magnitude approaching small solar outbursts, and unequalled on earth by anything less than a major volcanic eruption. Jupiter burst studies are commencing at AFCRL; instrumentation design and installation are nearing completion.

3.5 Radio Astronomy

In addition to the rather extensive probing of the moon by radar done in this country and abroad, efforts have been made to contact Venus and the sun by radar. Of the two early attempts to contact Venus, one by the Lincoln Laboratory of MIT was reported successful, and another by Dr. John V. Evans, at Jodrell Bank was reported unsuccessful. Because of the very weak signal received by Lincoln, on the order of 20 db below noise, the data processing required was quite extensive, and the results are therefore not as obvious as they might be; in fact they were later renounced. Subsequent experiments by the Jet Propulsion Laboratory, Lincoln and

TABLE 3. Frequencies of Jovian Radio Emission

Frequency Mcps	Observer	Date
14	Gardner and Shain	1955-1956
18	Gallet	1956-1957
18	Carr, Smith, Pepple and Barrow	1957
18.3	Shain	1950-1951
19.6	Gardner and Shain	1955-1956
20	Gallet	1956-1957
21.1	Smith and Douglas	1957
22.2	Burke and Franklin	1955-1956
26.6	O.S.U.	1956-1957
27	Wells	1955
27	Gardner and Shain	1955-1956
38*	Smith	1952-1953
43	Mukherjee	1957
81.5*	Smith	1955

*No radiation detected

Jodrell Bank were considered quite successful. A similar experiment was performed by Stanford University on a solar measurement, and once more the radar returns were substantially (-40 to -50 db) below noise. This, however, represents the longest range radar detection on record, the range being about 9.3×10^7 miles and the round trip time being about 1000 seconds. The experiment has been successfully repeated by Lincoln also. It is hoped that the Arecibo radar mentioned earlier will provide the necessary power to perform more precise planetary and solar measurements.

4. EQUIPMENT FOR RADIO ASTRONOMY

J.P. Mullen

In this section the instruments used in the study of "Astronomy by Radio" will be briefly discussed. The unusual arrangement of the words in the previous sentence has been made to illustrate a point which, it is hoped, will be made throughout the report. This point is simply that radio astronomy is basic astronomy observing the radio portion of the astronomical spectrum rather than the optical of the early and present day observers. With this in mind, the subject of instrumentation may be developed further.

The first step in any program of scientific measurement is to determine the parameters to be observed, and to design the instrumentation accordingly. In the

case under consideration, that of reception of radiation from emitting sources, the parameters to be measured are frequency, polarization, position, size and intensity of the emitted radiation. The sources may be generally broken down by size, into discrete and distributed sources of radiation, and the radiation by categories of general mechanism into four general types of emission, which we will call thermal, line, synchrotron, Cerenkov, and plasma radiation.

It is estimated that of the hydrogen, which forms the vast majority of the bulk of the universe, 10 percent is ionized and 90 percent un-ionized. Thermal radiation is that produced by ionized hydrogen surrounding intensely hot stars. These areas, known as the Hydrogen II regions, depend for their emission mechanism on the free-free transition, follow a spectral law where flux $= \alpha f^n$, where f = frequency and n is a number near 2 or 3. This phenomenon is the best understood mechanism of astral radiation; while it has been reported as being only in a limited number of nebular sources at microwave frequencies, they dominate the radio sky.

Line radiation is that which produces a discrete frequency or frequencies, rather than that produced over a continuous spectrum, as is the thermal radiation discussed just previously. The only interstellar line radiation discovered and verified is that of neutral hydrogen (Hydrogen I), which has a line emission at 1420.4056 Mcps. The emission is generated by the transition between two closely spaced energy levels in the hyperfine structure of ground or lowest energy state. This process, in a single atom, generates a single precise frequency. Naturally, in the real world, one does not look at an atom but at a cloud of gas some thousands of parsecs in depth, (a parsec is about 3.26 light years, or 19.2 trillion miles) traveling in a spiral motion, so that the line suffers broadening and Doppler shifting. Indeed, it is the Doppler shifting that enhances the value of observing the line spectrum. While the only line source detected thus far is that of neutral hydrogen, attempts have been made to receive the deuterium line at 327 Mcps; the small volume and thereby small output (the ratio of deuterium to hydrogen on earth is to 1 to 5000) must await far more sensitive receivers and much larger antennas.

Nonthermal emission is that which does not obey the thermal laws of flux $= \alpha f^n$ noted earlier. The vast majority of the celestial sources fall into this general category and, in fact, follow a law of flux $= \alpha\ 1/f^n$, where n is some quantity between zero and three. The mechanism of generation are not completely understood; however, two mechanisms are sufficiently well established to bear comment. One of these is the synchrotron process, where visible and radio waves are produced by high energy electrons in magnetic fields.[18]

This radiation is held to be present in the galactic corona, in the galactic plane, and also in the Crab Nebula. One of the characteristics of synchrotron radiation is a frequency spectrum dependent upon the energy spectrum of the electrons, and another is polarization of the E vector parallel to the radius of curvature of the

electron orbit. This polarization has been detected by optical means in the Crab Nebula. The Soviets have made recent claims of detecting linear polarization at 3200 Mcps, and the Naval Research Laboratory at 9500 Mcps. Since radiation at the lower frequencies is subject to Faraday rotation our best expectation of measuring polarization occurs at the highest frequencies. It is indeed unfortunate that the flux at these frequencies is so much less (flux = $\alpha \frac{1}{f^n}$).

Another form of nonthermal radiation (named after its claimed discoverer, Cerenkov) is that which is induced when a relativistic particle enters a medium having a refractive index greater than 1. The particle continues and radiation is given off because the electric and magnetic fields surrounding the particle are retarded, since their velocity through the medium cannot exceed C/n where n is the index of refraction, and C is the velocity of light. This radiation, discovered in nuclear energy studies, has been offered as a phenomenon to which "a great deal, perhaps most, of the nonthermal radio spectrum may be attributed".[19]

The radio spectrum of the sun's radiation runs from about 30 Mcps to the near infrared. Of this, up to 30,000 Mcps is considered due to nonthermal causes. Polarizations observed in solar radiation have been random, circular, partially polarized circular, elliptical (rarely), and extremely rarely, linear.[20]

Plasma oscillations are also believed present in the sun. Radiation from a plasma can be caused by deceleration of particles due to an atomic encounter, energy released due to recombination, Cerenkov radiation when a relativistic particle enters a medium with index of refraction greater than one, or unstable oscillations arising from electron density gradients existing in nonuniform plasmas. The frequency of these oscillations is dependent only upon the electron density, and the electron density present in the solar corona is sufficient to yield the frequencies measured. Objections to the theory have been proposed by Ryle and others. The idea remains as a possibility, however, until more evidence can be obtained.[21]

To recapitulate, the mechanisms generating radio frequency energy by solar and stellar processes are understood vaguely, if at all; they can, however, be divided into arbitrary classes of thermal and nonthermal. The thermal is loosely defined as that having a flux which increases exponentially with frequency, and nonthermal defined as that having a flux which decreases with frequency. A special case, really neither thermal nor nonthermal, is that of line radiation. Thus far the only one detected is the 21-cm line of neutral hydrogen. The thermal and hydrogen line processes are best understood; the nonthermal processes are believed to be synchrotron, Cerenkov, plasma, or combinations of these processes. Fortunately, despite the lack of agreement on their cause, the symptoms are well known, and it is these that determin e the characteristics of the instrumentation.

The characteristics of the radiation to be received are as follows: The general type of radiation observed is a noise-like signal extending from vlf to near infrared

with the consideration that atmospheric and ionospheric considerations normally limit the useful spectrum to the range between a few megacycles and forty or fifty kilomegacycles. If, however, the equipment is placed above the atmosphere and/or ionosphere (for example, in a satellite) these restrictions do not apply. As the vast majority of the sources are nonthermal, their output at high frequencies (centimetric, for example) is quite low and centimetric receivers must be extremely sensitive. Receivers for low frequencies, say, in the tens or hundreds of megacycles, may be relatively insensitive. A very vital portion of the frequency spectrum is that of the hydrogen line. This line frequency, basically 1420.4056 Mcps, suffers doppler shifting both from the motions of the spiral galaxies (including our own) and the motion of the earth, up to thirty odd megacycles, corresponding to a relative velocity of 7000 km/sec, about 1/43 of the speed of light. Galactic surveys, however, need only about a megacycle (plus or minus) to map the hydrogen line and its doppler shifts. Except at centimetric wavelengths, polarizations are so distorted by Faraday effect as to be undetectable in stellar work. Solar equipment, however, may be designed to register polarizations. The Cornell University Polarimeter, for example, operates on 201.5 Mcps and has yielded much useful data.[20]

The specification of sensitivity is a difficult one since the question is not simply how much sensitivity one must have (the answer is obviously all one can get), but rather what is the lowest sensitivity that it is feasible to build into a receiver. Here is a fairly arbitrary situation but, in general, the ability to detect a difference of a few degrees Kelvin would be satisfactory for most applications. The Muller-Leiden hydrogen-line receiver, probably the most famous hydrogen-line receiver in the world, has a consistent sensitivity of .73°K. The traveling-wave-tube radiometer at AFCRL has a sensitivity of 1°K, and the NRL maser X-band radiometer is sensitive to temperature changes of .04°K. The Harvard College Observatory has measured a sensitivity of .014°K using a maser at 1420 Mcps. These figures, it will be seen, are quite arbitrary since a complete specification of sensitivity must define bandwidth and integration time. These numbers will, however, serve as a general example of the detection sensitivities available.

In the simplest type of radio telescope receiver, a conventional superhet, the sensitivity is largely determined by the noise figure, as in the conventional communications receiver. The noise figure can be defined as the ratio of noise power out of a network to that expected from an ideal noise-free network. Consider a noise-free network having as its input P_i. This input power can be represented as $P_i = KT_1B$ which is the thermal power developed in an element heated to an absolute temperature T_1. B is the bandwidth in cycles; T_1 is in °Kelvin; and K, Boltzman's constant, is equal to 1.37×10^{-23} joules/°Kelvin. Since K is a constant, and B is a constant (for any given network) the power P_i may be represented by its equivalent noise temperature T_1. Consider, then, a network having gain G, and producing

within itself a noise power P_N, having at its input terminal a signal power P_i. The network noise figure may then be represented by

$$F = \frac{\text{output noise power}}{\text{input noise power}} = \frac{P_iG + P_N}{P_iG} = \frac{KT_1BG + KT_NBG}{KT_1BG}$$

(where T_N is the equivalent noise temperature of P_N) and

$$F = \frac{T_1 + T_N}{T_1} = 1 + \frac{T_N}{T_1}.$$

T_1 is generally taken as the ambient temperature, 290°K for an uncooled network. The noise figure then becomes

$$F_N = 1 + \frac{T}{290^o},$$

where T is the effective or excess noise temperature.

Table 4 shows the relationship between the effective noise temperature T and the noise figure (or factor) in decibels

TABLE 4. Effective Noise Temperatures and Noise Factors

F_N		T
db	ratio	°Kelvin
0	1.00	0
1	1.26	76
2	1.59	171
3	2.00	290
5	3.16	627
8	6.31	1540
10	10.0	2610

Until recently, it was customary to estimate the effective noise temperature of a receiving system on the basis of the first stage alone, since its contribution, amplified by all the succeeding stages, generally swamped out the effects of the other stages. The overall excess temperature of the receiver can be represented as follows:

$$T_{receiver} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1G_2} + \frac{T_4}{G_1G_2G_3} +$$

where the subscripts refer to the effective noise temperatures of the stages. For some characteristic values, assume a first stage noise temperature T_1 of 400°K,

a mixer temperature T_2 of 900°K, first and second i-f temperature T_3, of 40°K with gains of 10, .25, 100, respectively. The temperature is then

$$T = 400 + \frac{900}{10} + \frac{40}{10 \times .25} + \frac{40}{10 \times .25 \times 100} +$$

$$= 400 + 90 + 16 + .16 \text{ and so forth.}$$

It will be seen that by far the major contribution is that of the rf preamplifier. If the noise temperature of the rf preamplifier were say, double that in our example (still a respectable noise figure), the contribution of the mixer and i-f amplifier would be negligible. It is also evident that if the preamplifier noise figure were halved, the importance of the following stages in determining overall noise figure increases.

This cursory view of the noise and sensitivity characteristics of the receiver has neglected the effects of the image channel, and of the system losses. We can dispose of the image channel readily if we consider only receivers where the image is either attenuated by a filter or is used as part of the signal input. In the former case it can be ignored, in the latter, it contributes to both signal and noise, so the effective B for the system is doubled.

If we consider that our antenna, immersed in sky temperature T_1, is connected to the receiver by a cable having a loss of α where α, the loss factor is on the order of .10 to .30 (-10 to -5db), then the minimum detectable temperature of the radio telescope will be:

$$T_{min} = \frac{T_a + T_o (N_o - 1)}{\alpha \sqrt{B\tau}}$$

Where T_a = antenna temperature
T_o = 290°K
N_o = noise figure
B = bandwidth
τ = integration time

It should be pointed out that losses may be minimized in the equipment by proper design, but that losses are induced by the molecular absorption of oxygen and water vapor, by the ionosphere, and by galactic background. These, fortunately, are frequency sensitive and one is frequently able to avoid them by judicious use of frequency. The simple radiometer, consisting of an antenna, a receiver, and an indicator, is thus sensitivity limited by its noise figure, its bandwidth, and most of all by its stability. As was earlier pointed out, the sensitivity is related to $(B\tau)^{-\frac{1}{2}}$, and therefore

the gain change in a specified time must be small compared with this quantity. For a bandwidth B = 1 Mcps, and for τ = 1 sec, the maximum permissible gain fluctuation is one part in 1000. This requires even greater stability in power supply voltages and environmental temperatures. One way of calibrating the instrument is to switch in a load at a calibrated temperature every now and then, which will indicate any long-term drifts. Even with this, the instrument is subject to glaring inaccuracies due to fast fluctuations, and, even on slow drifts, the process complicates the analysis of the data.

A method of reducing the effects of gain fluctuations was introduced by R.H. Dicke[22] at the M.I.T. Radiation Laboratory. The Dicke radiometer, as it has been called, switches the receiver input at a regular rate between the antenna and a standard load; the receiver output is detected, and its component at the switching frequency is amplified and fed to a synchronous detector (synchronous with the switching) after which it goes to a recorder. The advantage of this receiver is that it measures the difference between the antenna temperature and the temperature of the load. Since only variations at the switch frequency appear in the output, gain changes and receiver noise are substantially reduced. It is necessary to maintain the temperature of the reference load to a good tolerance, but the gain fluctuations may be reduced by a factor of $T_r/(T_a - T_s)$ where T_r is the excess receiver temperature, and T_a and T_s are the antenna temperature and the load temperature, respectively. For the example cited previously, that of the allowable gain variation of 1 in 1000, one in eighty will yield the same result. This is such a significant improvement that, despite the disadvantage of being connected to the antenna only half the time, it is the universally accepted standard form of microwave radio telescope receiver. It will be seen that the closer together that T_a and T_s are made, the greater will become the advantage of the Dicke radiometer over the simple receiver, and the greater the sensitivity (all other things being equal) that can be obtained. Because of the reduction the receiver noise effects, the Dicke receiver is generally used at microwave frequencies, that is, above 1000 Mcps, where receiver noise is dominant. At lower frequencies, however, the receiver noise is generally very low compared with the antenna temperature. A variation on this scheme has been developed by Ryle and Vonberg, where a variable noise source is automatically adjusted for zero receiver output. The noise source control current is metered and it is this current which is the indicator of the received signal. This is a very stable and self-calibrating system which is common in lower frequency (meter wavelength) surveys.

Hanbury Brown[23] points out that at 20 Mcps the receiver noise becomes negligible, since the sky has a brightness temperature (roughly equivalent to T_a) of 50,000°K or more, while at 3000 Mcps, the receiver noise dominates; sky temperatures may be near 1°K, and N might be about 8. Under these circumstances, receiver noise influences the result by a factor up to 10^5 greater than in the lower frequency case.

As the history of astronomy by radio is related to that of World War II electronics, it followed very naturally that the war surplus radar and communications equipment and techniques should fall into the hands of the astronomers after their war-like purposes were ended. Radar antennas and low-noise techniques were most valuable, and transmission lines were a close second. A particular example is the German Wurzberg antenna, 7½ meters in diameter, which, though designed for a 500 Mcps radar, was constructed with such tolerance that it was good to 21 cm. It was not long, however, before the needs of the astronomers far outstripped the capabilities of the radar equipment, years ahead of its time though it was. The sensitivity and stability of the military equipment as well as the collecting area of its antennas were adequate at first, and then became inadequate by orders of magnitude. The equipments were first used unimproved, unmodified, then modified and finally cannibalized with only a few of the components surviving.

After the war surplus had done its work, development work of a fairly limited nature was accomplished by the government and universities of a few foreign countries, some with industrial sponsorship. In our country, by far the major impact was made by government funding through the Office of Naval Research. This funding is now quite restricted, and it is plain that some government funding is still needed, for the commercial potentialities of Radio Astronomy equipment are not large, and university funding has always been limited.

Next we will discuss briefly the traveling-wave tube radiometer of the Air Force Cambridge Research Laboratories, the maser equipment of NRL, and two multi-channel hydrogen line receivers. (In a later section, the phase switched interferometer receiver will be mentioned.) The AFCRL radiometer, developed by the Propagation Sciences Laboratory, is a Dicke-type C-band receiver using a three-stage traveling-wave-tube amplifier in a tuned radio-frequency configuration.[24] It is not common, even in this day of the traveling-wave tube, to find a high sensitivity receiver in other than superheterodyne configuration, but the advantages of this one are quite pronounced, for it permits use of an 800 Mcps bandwidth. Since sensitivity is proportional to the square root of bandwidth and integration time, a 4-second integration time can yield a sensitivity of less than a degree Kelvin, about five times as good as a conventional superhet might give.

The NRL maser radiometer is a Dicke-type superheterodyne operating from 8900-9500 Mcps, using a ruby maser as an rf amplifier stage. The maser, a fairly recent development, owes its name to the first letters of "microwave amplification by stimulated emission of radiation" and operates as follows: a crystal is placed in a magnetic field and cooled to a temperature on the order of a degree Kelvin. The NRL three-level maser uses a ruby ($Al_2O_3 . 01Cr_2O_3$) as the paramagnetic element. The changing levels of the Cr^{+3} ion in the ruby are the amplifying mechanism. In the three-level maser the electron is driven by a "pump" oscillator from the first,

or lowest energy level to the third energy level. When stimulated by a weak signal, it falls to the second level, giving up its energy to the signal in the process. From the second level the electron slowly falls to the first, the crystal absorbing the energy in this process, after which it is ready for pumping again. The NRL maser consists of a ruby crystal mounted in a microwave cavity which is resonant at the signal and pump frequencies, 9400 Mcps and 23.1 Mcps, respectively. The cavity was set in a magnetic field of several thousand oersteds, and was cooled to about a degree Kelvin. This was accomplished by floating the cavity in liquid helium and placing the device in a Dewar flask (thermos bottle). From this front end they measured an equivalent noise temperature of $.4^{o}K$ with 5 seconds integration. Unfortunately, the back lobes of the antenna contribute a large amount of noise temperature to the system ($\approx 80^{o}K$) and the device must be mounted at the feed horn to reduce line losses, before the maser front, which becomes dominant with very low noise, ends. The gain-bandwidth product of the maser was 50 Mcps; that is, it had a gain of ten over a 5 Mcps bandwidth, which was the i-f bandwidth of the system. For higher microwave frequencies, the maser and related devices can yield a definite increase in sensitivity. Sidelobe temperature and noise in other portions of the receiver can however combine to reduce its effectiveness. The cooling problem can be a nuisance also.

Two very advanced receivers for hydrogen-line observations are those at Dwingeloo, the Netherlands, and at the Carnegie Institution in Washington, D.C. This latter is a 54-channel superheterodyne, having a sensitivity of about $2.4^{o}K$. The channels are 12 kcps wide, spaced every 18.9 kcps apart to cover $1420 \pm .5$ Mcps. This permits doppler profiles of velocities, with readings every 4 km per sec. The zero line, however, appears to change, requiring frequent attention, and several other drifts within the system appear to require calibration every few days. The other advanced receiver considered worthy of special mention is the 8-channel hydrogen-line receiver at the Dutch radio observatory at Dwingeloo. This receiver, designed by C.A. Muller, has received widespread acceptance as the finest hydrogen-line equipment in existence. Such a sterling reputation is based upon its stability, utility, and ability to run for months without maintenance, and to be operated by unskilled personnel.* The receiver is a Dicke type using as standard a relatively quiet frequency, that is, a reduced antenna temperature. The receiver, then, switches between the quiet background and the unknown source. In order to eliminate the half-time duty cycle of the Dicke system, while the receiver is looking at the standard, another channel is looking at the source. Since any difference in signals appears in the output, all corresponding channels must have identical gain. All in all, the equipment is a quadruple conversion, 8-channel affair using about 700 tubes. The

*The receiver is operated by students after a very brief orientation lecture.

front end is a conventional mixer stage, and a parametric amplifier stage is currently being designed for it. Sensitivity without the parametric front end is about $.7^{o}K$.

It was earlier stated that the three fundamental parts of a radio telescope are an antenna, a receiver, and some recording device. It was also stated that in general, the antenna temperature is considered to be that of the area of sky at which the antenna is pointed. These two generalities understate the importance of the antenna to the radio astronomer. The characteristics of an antenna that are of first interest to the astronomer are gain and resolution. Gain is defined as the apparent increase in power of an antenna over an omnidirectional radiator and can be defined as:

$$G = 4\pi AE$$

where A = cross-sectional area in square wavelengths

E = efficiency factor, 100 percent for perfect uniform illumination of a perfect parabola, more commonly taken as 55-65 percent.

Here it will be seen that the larger antenna areas (in square wavelengths) will have the higher gains at the same time, the solid angle of the antenna beam can be related to the gain by the number of square degrees in the beam compared with the number of square degrees in a sphere.[25]

$$\theta = \frac{41,253}{G}$$

where θ is in square degrees, G is dimensionless.

Since antenna patterns are not normally given in square degrees, a more useful approximate formula has been given by Ruze.[26]

$$G = \frac{44,000}{BhBv}$$

where Bh and Bv are the half-power beamwidths in the horizontal and vertical planes.

Unfortunately, it is very difficult to illuminate an antenna reflector in such a way that no sidelobes occur. Sidelobes are generally caused in three ways: by energy spilling over the edge of the reflector and being reflected from the terrain, from energy leaking through the reflector, and most significantly, by diffraction as the illuminating energy sees the discontinuity of finite reflector and the free space beyond it. These lobes, while they may be (and frequently are) reduced by a factor of several hundred below the major lobe, bring in extraneous energy from the blackbody radiation of the earth, for example, which arrives through the signal channel and acts, in fact, to reduce the signal-to-noise ratio. Good circular aperture antenna design puts about 85 percent of the power in the main lobe leaving 15 percent in the back and sidelobes. If these back lobes look at earth temperatures of $290^{o}K$, their contribution to the system temperature (assuming the source to exactly fill the main lobe) of $100^{o}K$ sees then:

$$T_A = 85\% \times 100^{\circ} + .15 \times 290 = 128.5^{\circ}K$$

$$T_{total} = T_a = T_1 = 128.5^{\circ}$$

We are indeed fortunate that in frequency regions where sidelobes are worst, the sky temperature T_A is in thousands of degrees Kelvin, and the sidelobe contribution may normally be neglected. Some very significant cases have arisen, however, where the back lobes did in fact cause serious errors.

When the source fills only a fraction of the main antenna beam, the antenna temperature becomes:

$$T_A = T_S \times \frac{\text{source area}}{\text{beam area}}$$

when the beam is narrower than the source, $T_A = T_S$.

4.1 Large Antennas and Small Tolerances

The radiation from a star which falls upon the earth is , by the natural process of isotropic radiation, diffuse, and it behooves one to intercept it with as large an antenna area as is practical. For this reason, as well as the resolution considerations discussed previously, the trend has been toward larger antenna areas. Perhaps the first of the truly large steerable parabolic antennas was that of the University of Manchester at Jodrell Bank. This instrument was designed to operate at or below 300 Mcps, but since its design, the importance of the 21-cm hydrogen line has become known, and considerable use has been made of it on that frequency. Now the matter of tolerance comes into view. It is generally accepted among astronomers that the antenna reflector tolerance cannot depart from its theoretical shape (in most cases, paraboloid of resolution) by a distance greater than $\pm \lambda/16$. An RMS deviation of this order yields about 56 percent aperture efficiency. The Jodrell Bank dish, on the other hand, has deviations in the order of ± 4 inches, acceptable at 300 Mcps but leading to an aperture efficiency at 21 cm of about 30 percent. This aperture may be simplified by considering it made up of an illumination efficiency (generally 55 percent) and a form factor C, the resultant of these two being the aperture efficiency. This composite quantity can be defined as the ratio of the effective area to the active cross-sectional area of the antenna. This simple analysis can be used only as long as the deviations are small, in the order of a quarter-wavelength or less. The major effects of excessive mechanical tolerances in the antenna then are gain reduction and increase of sidelobe level, and of these, the increased sidelobe level is by far the more important to the radio astronomer.

4.2 The Interferometer

It frequently happens that adequate signal-to-noise ratio can be obtained using an antenna of a given size, while the beam may be too wide to resolve discrete sources in the sky area under study. In such cases, an interferometer is sometimes useful. An interferometer, in its simplest form, consists of two antennas, spaced apart some distance D and connected to the same receiver. This instrument. looking at a point source, produces a series of fringes in an envelope whose width is that expected from the combined area of the two antennas, the width of the first few fringes being $\Delta\theta = \lambda/D$, where λ is the wavelength and D is the separation, both in the same units. It can be seen here that, using antennas which might yield 1° resolution, angular resolutions of minutes or even seconds of arc are theoretically possible. Cable losses and other real-life effects complicate spacing the antennas beyond about a few thousand feet, however, and ambiguity considerations make their operation fairly stringent. Still, the interferometer is a very powerful tool because of its resolution and ability to measure flux density (by a correlation of the maximum and minimum to the F transform of the intensity distribution).

One of the difficulties of the simple interferometer is that its output contains a steady-state component equivalent to the power received by either antenna from the source. The only other component is, of course, the fringes. It is highly desirable to get rid of the steady state term, for when a small source and a large strong one are close together, they appear as weak signals superimposed upon a strong one.

In order to eliminate the steady state component (often called the total power component), it has become conventional to switch in and out periodically a half-wavelength of line in one leg. This, in effect, performs a sector scan of the fringe pattern, and by synchronous detection at the switch frequency, only the varying component—that is, the fringe—appears in the output. The technique is thus reasonably similar to the Dicke system, in which it will be remembered, only variations in the switched elements appeared at the output.

4.3 The Mills Cross

The Mills Cross named after its inventor, B. Y. Mills of the Radiophysics Laboratory, Commonwealth Scientific and Industrial Research Organization, was originally two line-source antennas of considerable length, arranged in a cross. The receiver is switched so that the signals in the antenna first add, then subtract. If A represents the signal on the north-south antenna, and if B represents the signal on the east-west antenna, it can be seen that the magnitude of $A-B = A+B$ if either A or B is zero. As with the Dicke system, an output is recorded only when a difference

exists between the channels, which are respectively (A-B) and (A+B). A somewhat similar instrument has been built at Stanford University by Bracewell, for operation at a wavelength of 9 cm. This instrument, more properly called a crossed Christiansen array, consists of 16 ten-foot diameter paraboloids in each of the two legs of a cross. The 325-ft leg length yields a lobe width of 4' of arc, the 25-ft element separation yields a lobe separation of 44' of arc, and the 10-ft paraboloids yield an envelope of 2.5°. This instrument is used for solar maps and studies of strong sources.

4.4 Data Reduction

One of the most severe bottlenecks is the difficulty of reducing the output of the radio instrument to meaningful astrophysical data. The output of the instrument is normally an inked trace on a roll of paper tape. On this tape at intervals are timing marks and other calibration data. The data desired are frequently maps of background brightness, or velocity, or spectra. It can be seen that a recorder running at one foot per hour will every twenty-four hours produce 24 feet. Reduction of this data, using the best manual techniques, will require about 72 hours, or 9 working days. During this time another 216 feet of tape has been accumulated. It has been said jokingly that the vast majority of the tapes feed from the machine to the storage line to the wastebasket in fairly regular fashion. Certainly, an automated reduction procedure is eminently desirable. Ryle at Cambridge has been using a punched paper tape output on his phase switched interferometer, which is then inserted into the EDSAC computer where a month's data is processed in a few hours. Other than this, no serious attempt at machine data processing is known.

4.5 Summary of Instrumentation Techniques and Equipment

A brief discussion has been presented of the sensitivities of present day equipment, and the types and methods of astronomical measurement by radio.

It has been pointed out that for the first few years, cast-off equipment was taken from the radar and communications engineers and modified slightly at first, then extensively, for its new role. As the art progressed, the required sensitivities and and stabilities demanded new equipment designed from the ground up for its unique application. Some few of these are described.

Areas worthy of future effort are:

a) Special antennas for special tasks such as the 1000-ft antenna in Puerto Rico or the Cavendish synthetic aperture in Canada.

b) Assistance in stabilizing the receivers. The sterling reputation of the Dwingeloo receiver is the shining exception.

c) Assistance in machine data processing. Sympathetic skilled personnel are needed much more than just money. An IBM computer may analyze handwriting, but it would be useless to the radio astronomer unless accompanied by a programmer who understands radio astronomy. What the radio astronomer needs may vary from a simple rotary channel integrator to a magnetic-tape punched-card computer complex.

5. THE FUTURE OF RADIO ASTRONOMY AT AFCRL

A. W. Barber With J. P. Mullen

"Basic research is when you don't know what you are doing"—Charles Wilson, former Secretary of Defense.

In determining the optimum electronics research program for AFCRL, one is faced with a number of fundamental problems. First is the fact that in the past, the word electronics within the Air Force has usually connoted radar, communications, bombing and navigation systems. Development of these systems by the Air Force is being required less and less, and therefore requirements for research in these areas are modest at best. On the other hand, the electronics field has never grown more rapidly than during the past few years. When we analyze this dynamic growth, we usually find that one or more imaginative scientists have applied electronic techniques to a completely new area. The new frontiers of electronics such as radio astronomy and bio-electronics are by their very nature removed from the classical interpretation of the Air Force military mission. Thus we must begin to look at electronics as a tool or instrument to be applied in fruitful areas of interest to the Air Force.

This situation raises two problems: first, if we are to be in the forefront of electronics research, we must consciously establish work in new mission areas; second, we must broaden the scientific personnel of the Directorate. A dynamic radio astronomy program requires not merely skilled radio engineers but also skilled astronomers or astrophysicists. It is sincerely hoped that AFCRL can and will enlarge its efforts in new fields such as radio astronomy.

References

1. G. REBER, Cosmic Static, Astrophys. J., 91:621-624, June 1940.

   ________, Cosmic Static, Proc. IRE, 30:367-378, August 1942.

   ________, Earth Radio Astronomy at Wheaton, Illinois, Proc. IRE, 46, January 1958.

2. N. RYLE and D. D. VONBERG, Solar radiation on 175 mc/sec, Nature, 158:339-340, September 7, 1946.
3. L. L. McCREADY, J. L. PAWSEY, and R. PAYNE-SCOTT, Solar radiation at radio frequencies and its relation to sunspots, Proc. Roy. Soc. A190:357-375, August 12, 1947.
4. J. S. HEY, Solar radiations in the 4-6 meter radio wave-length band, Nature, 157:47-48, 1946.
5. J. L. PAWSEY, R. PAYNE-SCOTT, and L. L. McCREADY, Radio-frequency energy from the sun, Nature, 157:158-159, February 9, 1946.
6. D. F. MARTYN, Polarization of solar radio frequency emissions, Nature, 158:308, August 31, 1946.
7. E. V. APPLETON, Departure of long-wave solar radiation from black-body intensity, Nature, 156:534-535, November 3, 1945.
8. J. P. WILD, Australian J. Sci. Research, Series A 30:395 ________, ________________, 3:407, September 1950.
9. K. L. BOWLES, A radar experiment to study the parameters of the outer atmosphere, Rpt PM-82-5905, NBS Boulder Labs, 5 August 1959.
10. F. G. WATSON, Between the Planets, Harvard Press 1956. ________, op. cit., Table 19, p. 94.
11. B. YU LEVIN, Physical Theories of Meteors and Meteoric Material in the Solar System, Document F-TS-9228/V, Liaison Office, Technical Information Center (MCLTD), WPAFB, Ohio.

References (Contd)

12. I.C. BROWNE, J.V. EVANS, J.K. HARGREAVES, and W.A.S. MURRAY, Radio echoes from the Moon, Proc. Phil. Soc. (London), LXIX:901-920, 1956.

13. J. AARONS, Studies and measurements made of the solar eclipse of October 2, 1959, AFCRL 158, April 1961.

14 R.H. DICKE and R. BERINGER, Microwave radiation from the sun and moon, Astrophys. J. 102:375-376, May 1946.

15. J.H. PIDDINGTON and H.C. MINNETT, Microwave thermal radiation from the moon, Aust. J. Sci. Res. A2:63-77, 1949.

16. J.D. KRAUS, Impulsive radio signals from the planet Venus, Nature, 178:33-34, July 7, 1956.

17. B.F. BURKE and K.L. FRANKLIN, Observations of a variable radio source associated with the planet Jupiter, J. Geophys. Res. 60:213-217, 1955.

18. C.H. TOWNES, Microwave and radio frequency resonance lines of interest to radio astronomy, IAU Symposium No. 4, August 1955.

19. L. MARSHALL, Production of the sun's non-thermal radio emission by Cerenkov radiation, Astrophys. J. 124 No. 2, September 1956.

20. M.H. COHEN, The Cornell radio polarimeter, Proc. IRE, January 1958.

21. G.B. FIELD, Radiation from plasma oscillations, Astrophys. J., 124:555-570, November 1956.

22. R.H. DICKE, The measurement of thermal radiation at microwave frequencies, Rev. Sci. Instr., 17:268-275, July 1946.

23. R.H. BROWN, A symposium on radio astronomy at Jodrell Bank, Observatory, 73:185-192, October 1953.

24. J.P. CASTELLI, J. AARONS, C. FERIOLI, and J. CASEY, Absorption, refraction, and scintillation measurements at 4700 mcs with a traveling wave tube radiometer, Planetary Space Science, Pergamon Press, I:50-56, 1959.

25. J.D. KRAUS and H.S. KO, Celestial radio radiation, AFCRL-57-557, May 1957.

26. J. RUZE, Graphical determination of antenna gain, Rpt 8-9, Air Material Command, Cambridge Field Station, 6 February 1947.

AF Cambridge Research Laboratories, Bedford, Mass. Geophysics Research Directorate
RADIO ASTRONOMY—a SURVEY, by A. W. Barber and J. P. Mullen. January 1963. 30 pp incl. illus.
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